
Fuel Cell Vehicle Systems Analysis

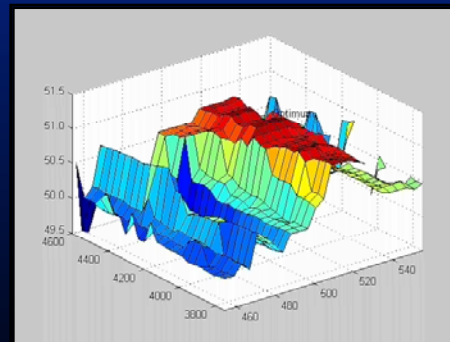
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National Renewable Energy Laboratory

May 20, 2003

DOE Hydrogen and Fuel Cell 2003 Annual Merit Review
Berkeley, California

Outline

- Objectives
- Approach
- Timeline of Highlights
- Accomplishments
- Addressing Reviewer Comments
- Industry Interactions
- Future Plans
- Summary

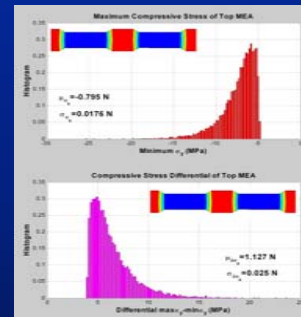
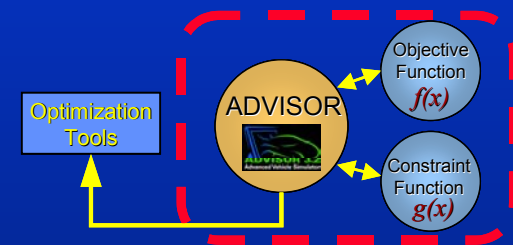


Objectives

- Provide DOE and industry with technical solutions and modeling tools that accelerate the introduction of robust fuel cell technologies
- Quantify benefits and impacts of HFC&IT development efforts at the vehicle level (current status evaluation)
- Understand sensitivity of fuel cell technical target values and provide recommendations to DOE program managers (future goal evaluation)

Approach

- Develop and link to existing component and vehicle models to enhance systems analysis capabilities
- Work with industry to apply robust design techniques, optimization tools, and CAE tools to overcome technical barriers
- Study benefits of fuel cell system and vehicle design scenarios and transfer to industry
- Assess impact of various technical team targets at component level



Highlights and Milestones

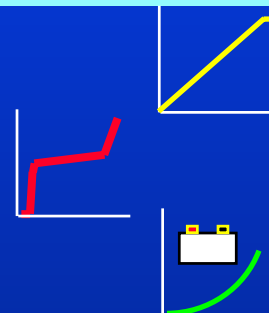
Planned
Completed
* = milestone

-
- | | |
|--------------|---|
| 6/02 | Presented FC response time study results at FutureCar Congress |
| 10/02 | Presented fuel cell system model evaluation study at 202 nd Electrochemical Society Meeting |
| 10/02 | Incorporated two detailed fuel cell system models into ADVISOR vehicle simulation program |
| 11/02 | Presented the Technical Targets Tool to DOE |
| 3/03 | Developed FEA models of fuel cell components and successfully demonstrated the application of robust design techniques |
| 4/03 | Presented results of 4 fuel cell system studies at ASME/RIT Fuel Cell Technology Conference |
| 6/03 | Results of gasoline reformer warm-up fuel economy impacts study to be presented at 2003 Future Transportation Technology Conference |
| 7/03* | Expand database of fuel cell components |
| 9/03* | Summarize the influence of key fuel cell program technical targets on fuel consumption reduction |
| 9/03 | Complete initial applications on reformer, end-plate design, stack pressure profile and high-temperature stack design |
| 9/03* | Publish technical report on methodology for applying robust design techniques to fuel cell components |

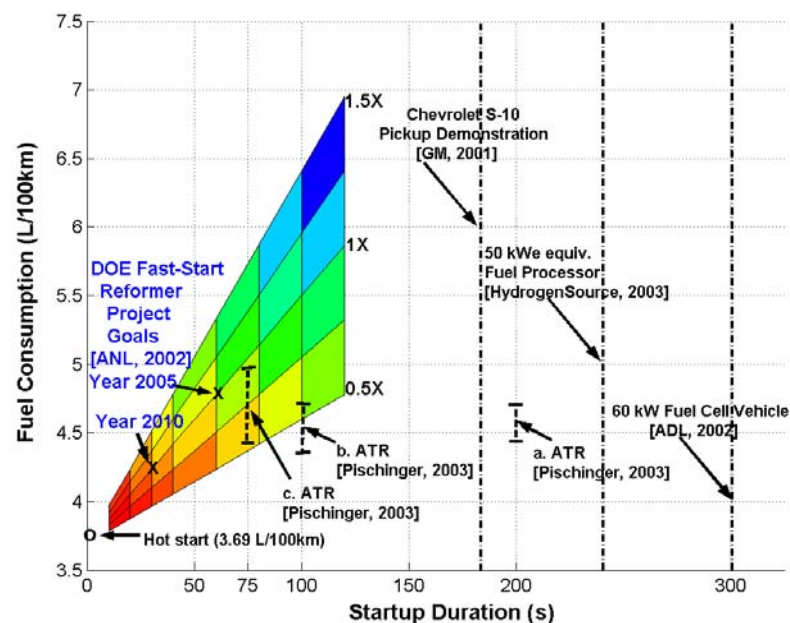
Accomplishments

Analyzed Fuel Economy Impacts of Gasoline Reformer Warm-up

- Allow warm-up period before FTP starts
- Design reformer and fuel cell system to provide minimum power requirements for FTP cycle with no energy storage
- Hybridize to balance out drive cycle requirements with achieving reasonable/efficient reformer startup time



Reformer Warmup Time (s)	Power (kW)	Cum. Raw Energy [Usable] (Wh)	SOC Window (%)	Nom. Battery Pack Total Energy (Wh)
30 s	13.5	15	20	75
60 s	13.5	45	20	225
195 s	25.7	158	20	790
10 min	25.7	658	20	3290
Toyota Prius	25	--	~5	1781
Honda Insight	6	--	~10	936
Honda Civic	n/a	--	n/a	864

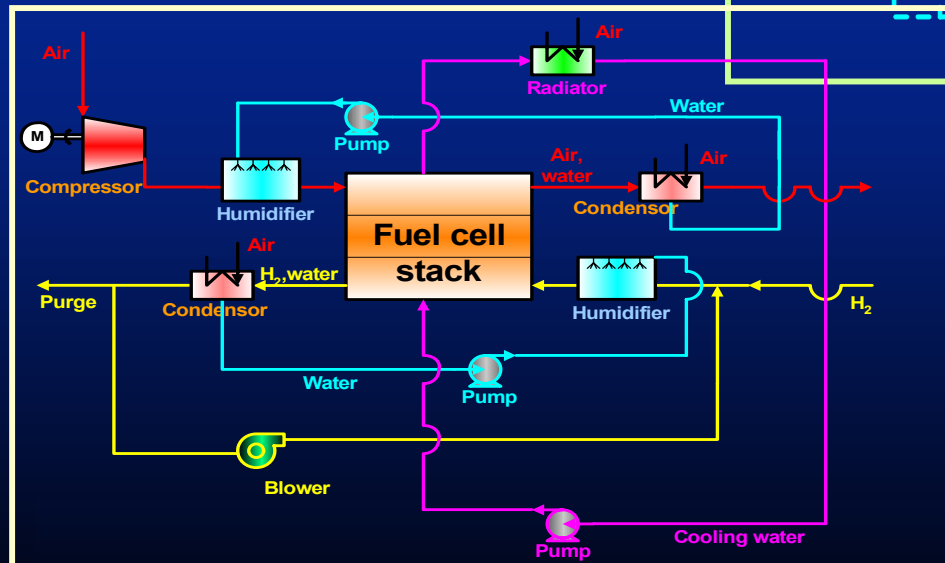
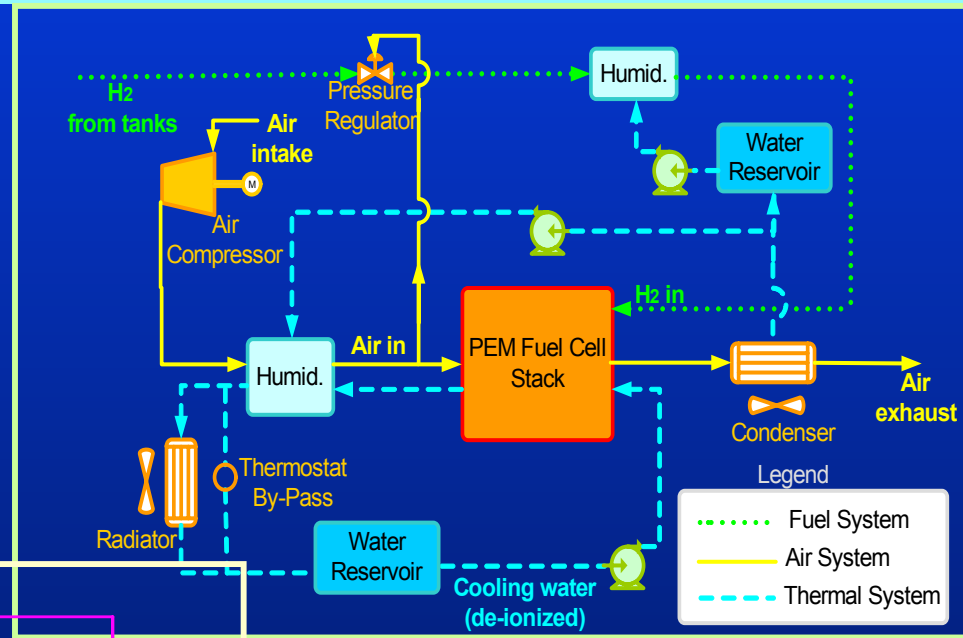


- Drive cycle traction power and energy demands satisfied with relatively small battery

- Fuel economy penalty significant if duration is long or fuel rate is high

Accomplishments

Two Detailed Fuel Cell System Models in ADVISOR



the Virginia Tech Model

the KTH Model

Accomplishments

Range of Model Complexity in ADVISOR

More Detail

KTH Model

- Springer et. al. fuel cell model
- thermodynamic library
- balance of plant components
- water transport in MEA

VT Model

- parametric polarization curve
- system thermal model
- balance of plant components
- variable operating pressure

Simple Polarization Curve

- defined current and voltage
- simplified balance of plant

Net Power vs. Efficiency

- single curve
- scalability



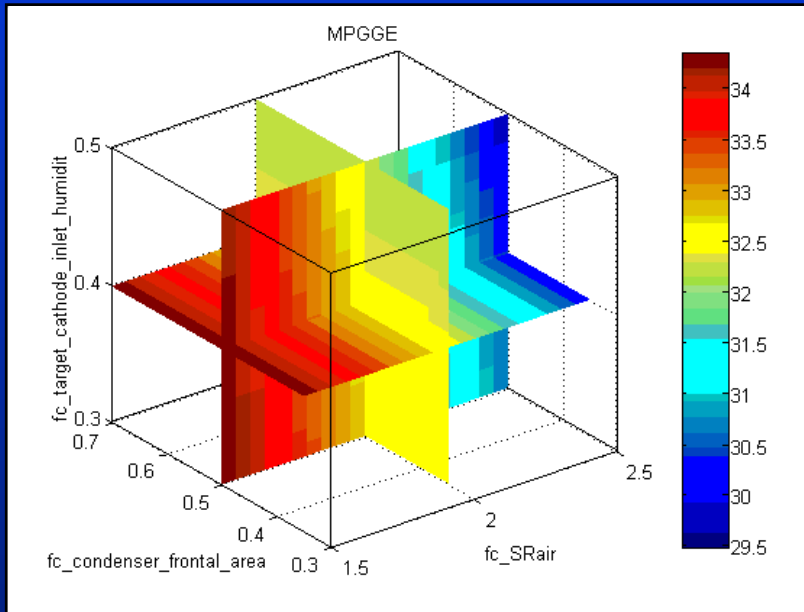
Less Detail

*** User-defined model ***

- configurable subsystem structure
- ability to link to fuel cell models in other tools (e.g. Saber, Simplorer,...)

Accomplishments

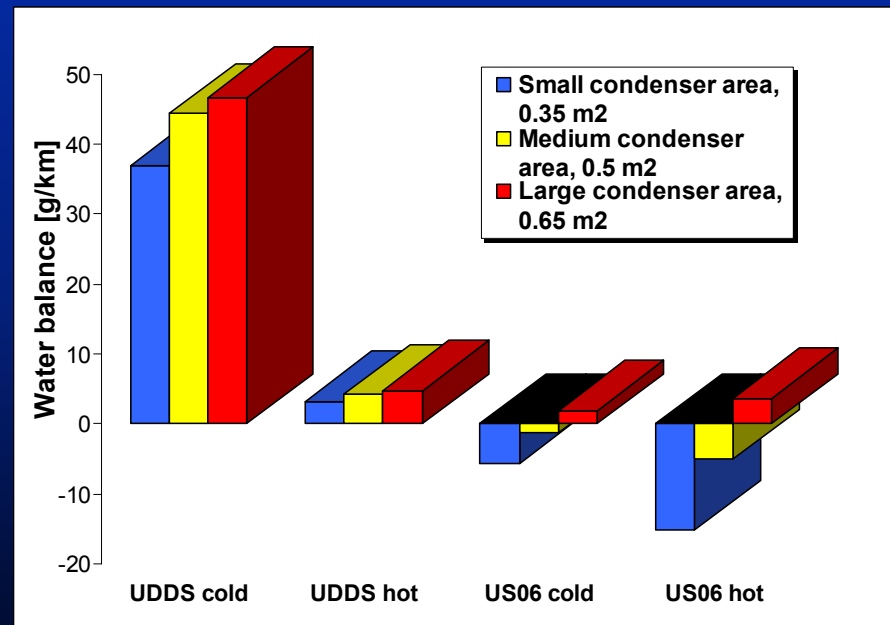
Water Balance Sensitivities Assessed



- Assessed water balance sensitivity in vehicle environment (drive cycles)
- Impact of condenser size and startup conditions quantified

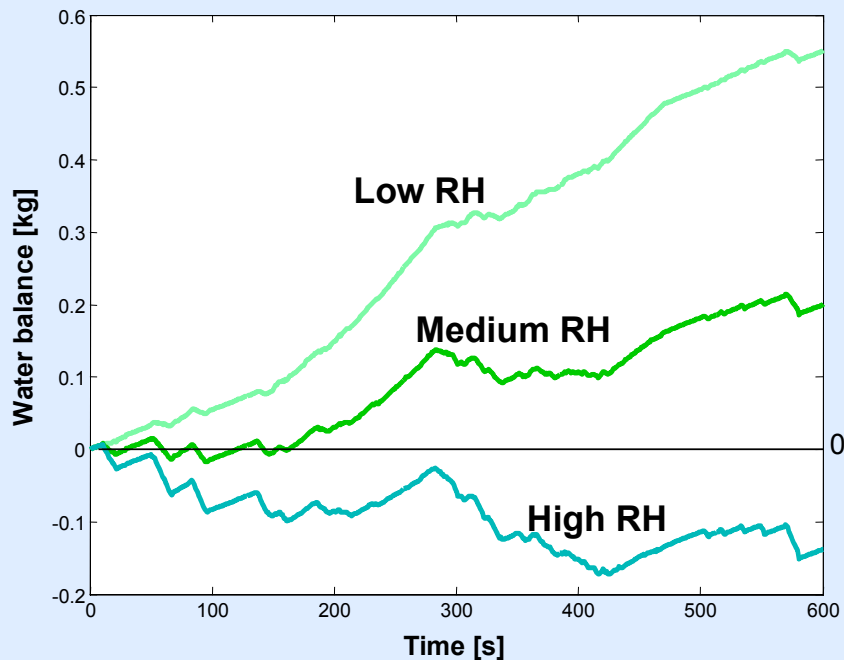
UDDS:
sensitive to cold/hot start

US06:
sensitive to condenser size



Accomplishments

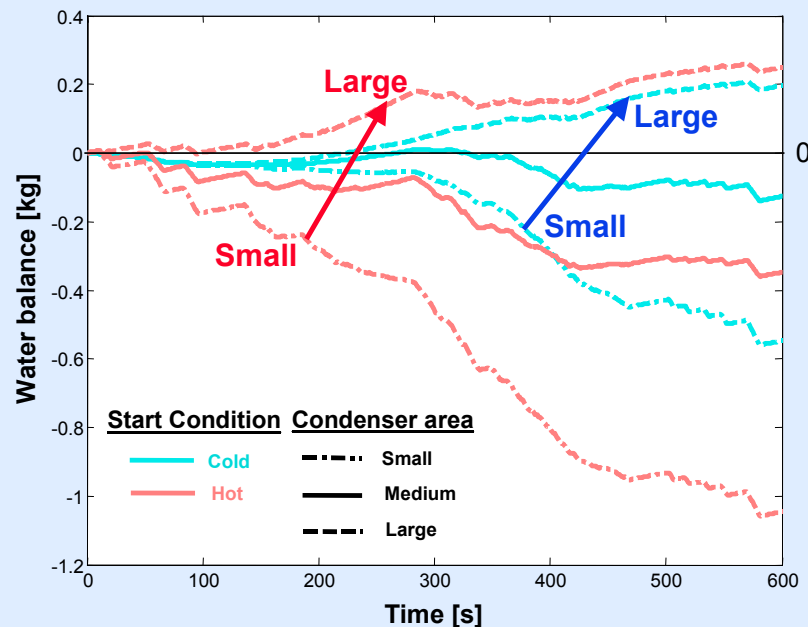
Water Balance Variability on the US06 Drive Cycle



Positive WB at low relative humidity requirements

Cathode
Rel. Humidity
Requirements

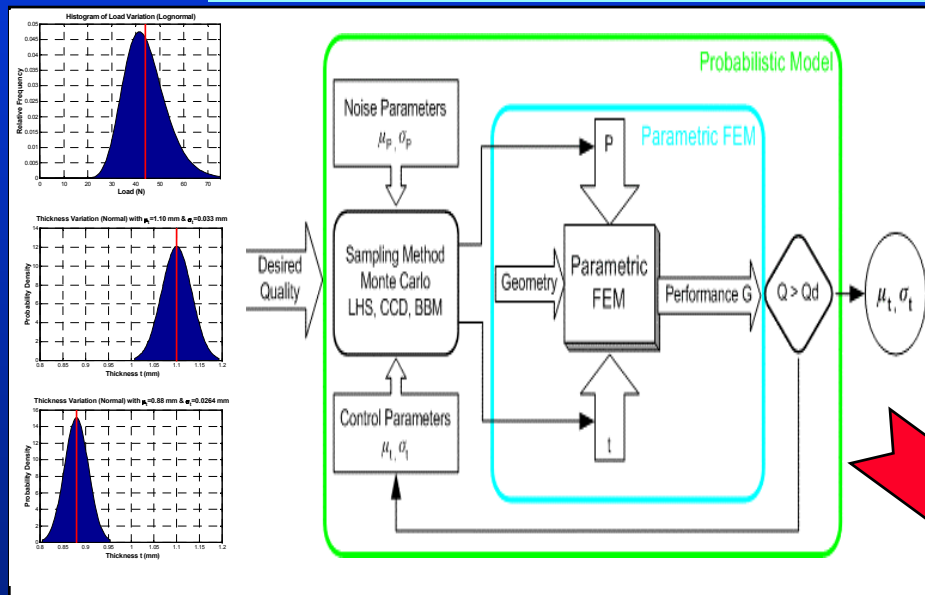
Condenser
Area



Better WB at low temperature operation

Accomplishments

Robust Designs of Fuel Cell Components

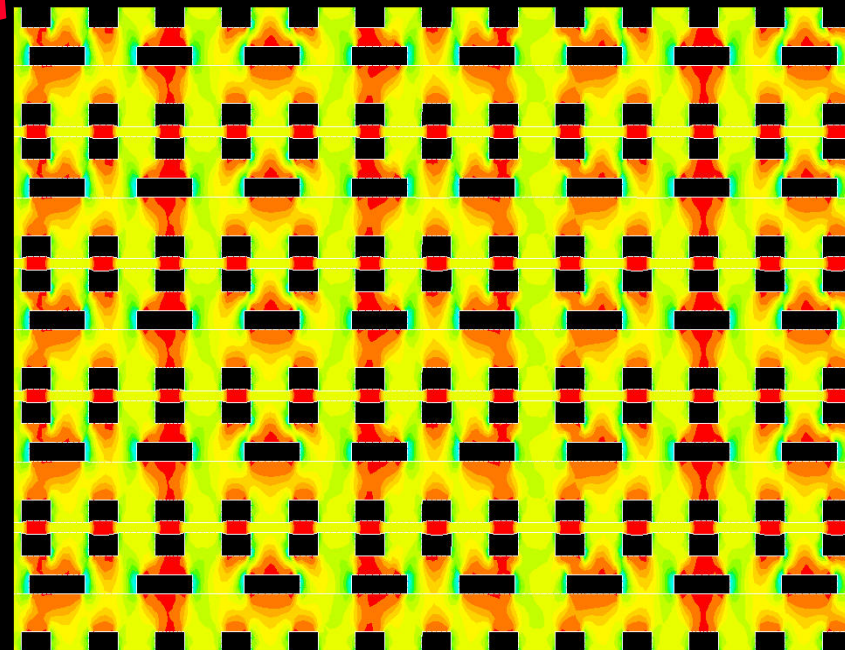


Collaborative effort with industry to apply robust design techniques to fuel cell components:

- Parametric FEA modeling
- Probabilistic design and optimization techniques integrated with FEA
- Topology optimization for reduced mass and improved pressure profiles

Solutions to real-world technical issues:

- improved thermal mechanical fatigue of ATR
- analyzed thermal efficiency of ATR
- improved pressure distribution within stack
- quantified sensitivity of design factors to non-uniform MEA pressure distribution



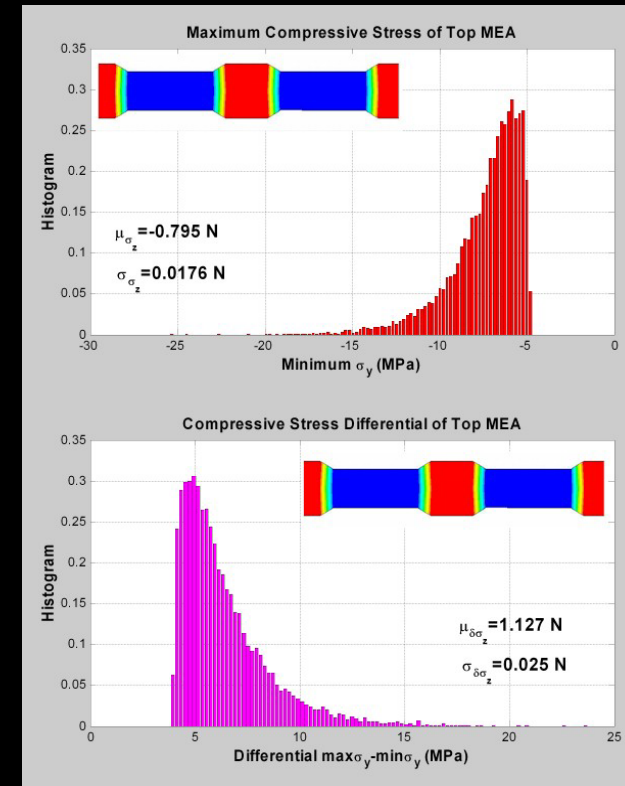
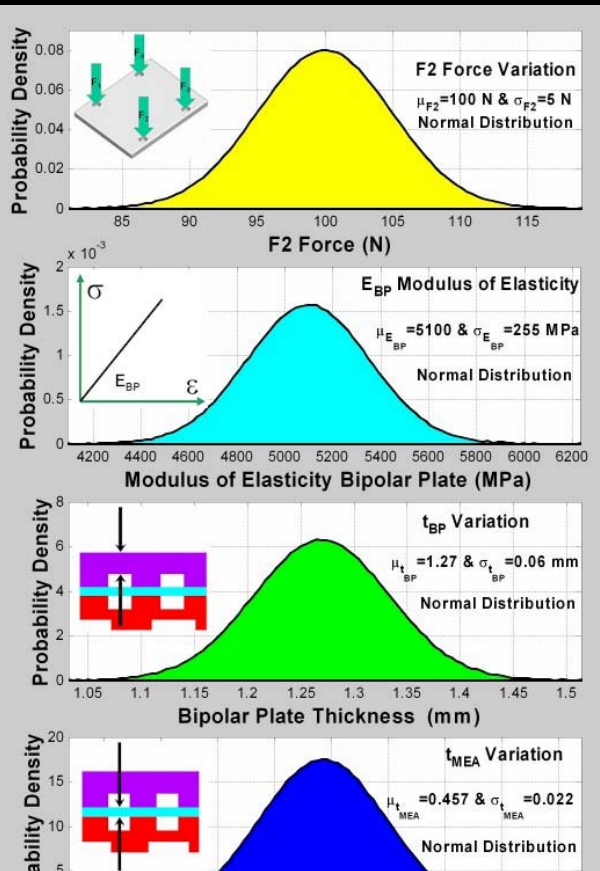
Accomplishments

Robust Designs of Fuel Cell Components

Statistical Distribution of
Material and Manufacturing
Variations

→ Parametric FEA Model
of Fuel Cell Stack

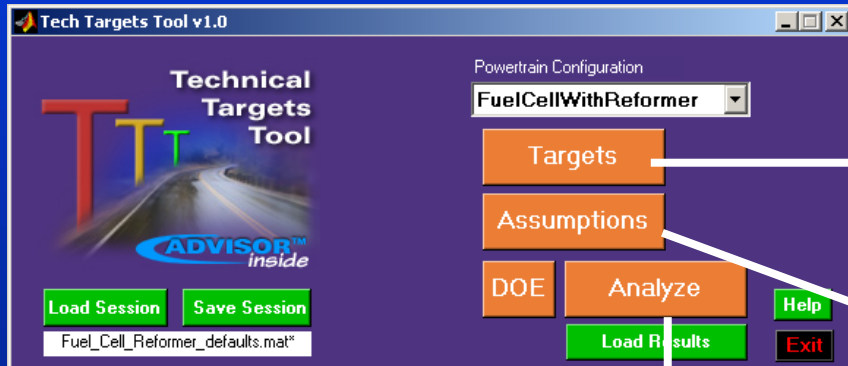
→ Statistical Distribution of
Output Performance
Measures



Published methodology for assessing the “Effect of Material and Manufacturing Variations on MEA pressure Distribution” (co-authored with Plug Power)

Accomplishments

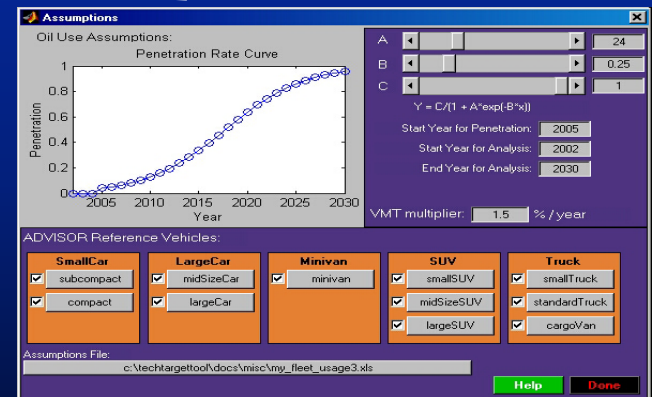
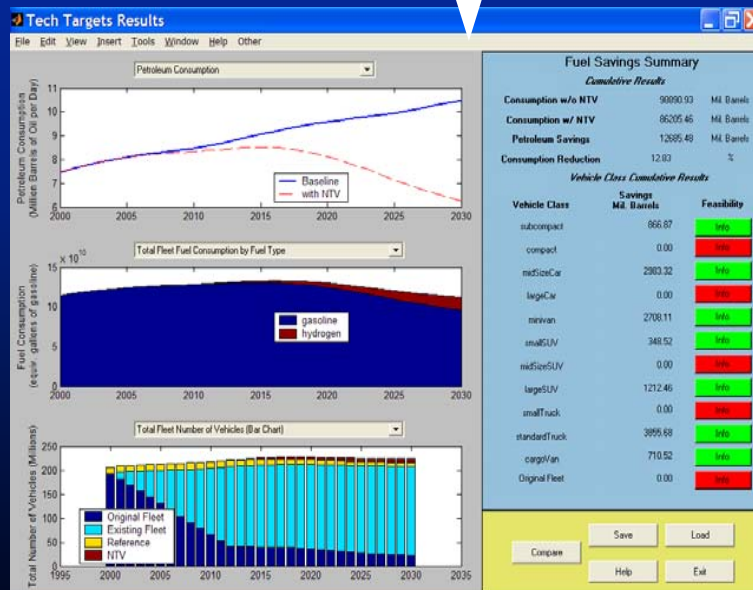
Technical Targets Tool Developed



Target Values



Model Parameters



Quantifies potential impact of DOE programs.

Accomplishments

T³ - A Repository for Component Targets

Targets

Individual Targets:

FuelCell fcsys

FuelCellSys FC_System_H2

Motor motcomp

ElecMachine EE_MotorGenerator

Electronics EE_PowerElectronics

EnergyStorage esssys

esssys ESS_DualMode

Vehicle vehsys

vehsys VEH_Vehicle

Tires tiresys

tiresys tiresys_targets.mat

Figure No. 3: Technical Target Table Edit Gui

Table 3.3.5. Technical targets: 50 kWe (net) integrated fuel cell power systems operating on direct hydrogen.

Characteristics	Units	2003	2005	2010	Up	Down
Energy efficiency @ 25% of rated power	%	59	60	60		
Energy efficiency @ rated power	%	50	50	50		
Power density - excluding H2 storage	W/L	400	500	650		
Power density - including H2 storage	W/L	TBD	150	220		
Specific power - excluding storage	W/kg	400	500	650		
Specific power - including storage	W/kg	TBD	250	325		
Cost (including hydrogen storage)	\$/kW	200	125	45		

DONE

Figure No. 3: Technical Target Table Edit Gui

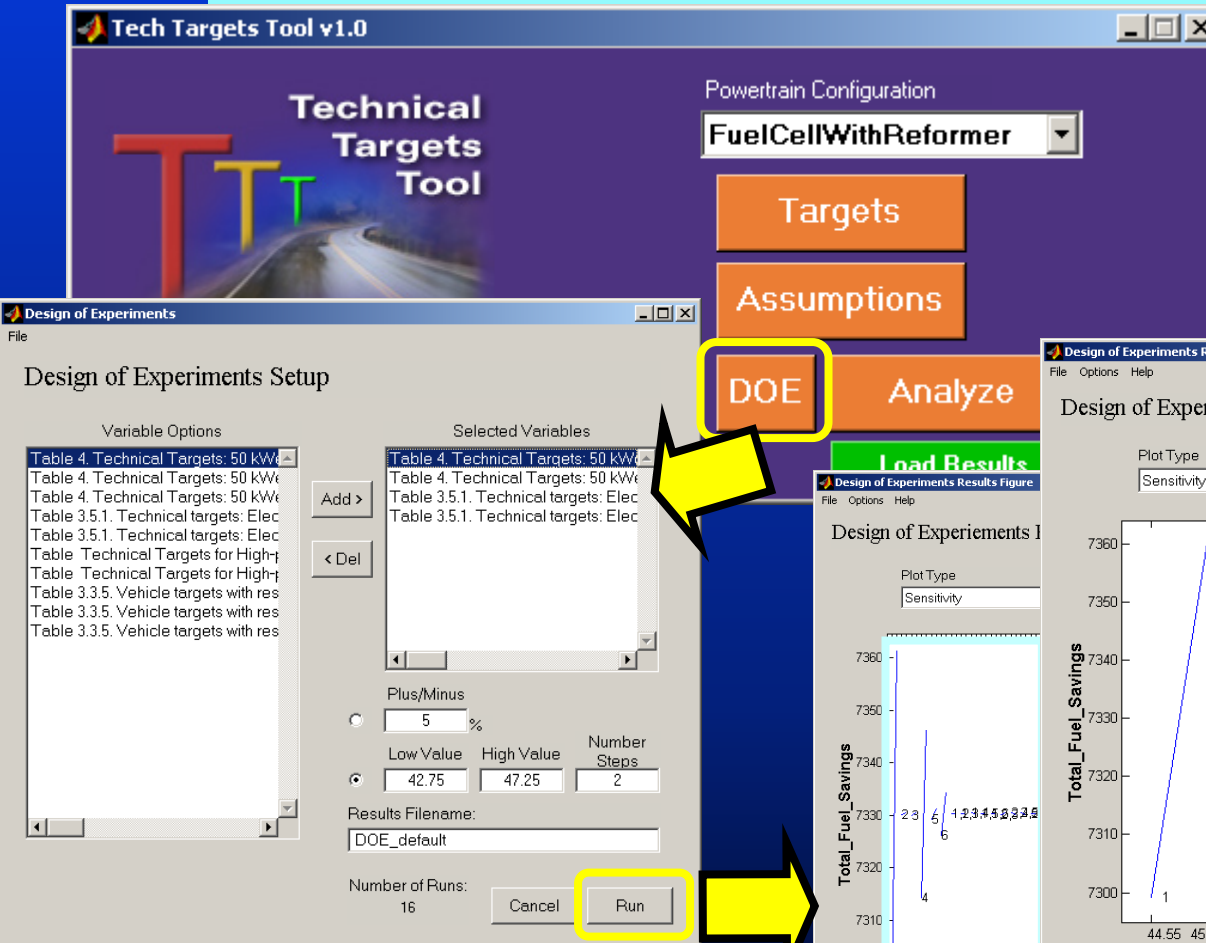
Table Technical Targets for High-power Batteries for Dual-mode Hybrid Vehicles

Characteristics	Units	2000	2004	2008	Up	Down
Power/energy ratio	W/Wh	39	30	30		
Specific energy	Wh/kg	21	15	17		
Energy density	Wh/L	24	20	24		
Cycle life @ min delta E	cycles	100	2500	2500		
Calendar life	years	5	10	10		
Cost	\$	2200	500	400		

DONE

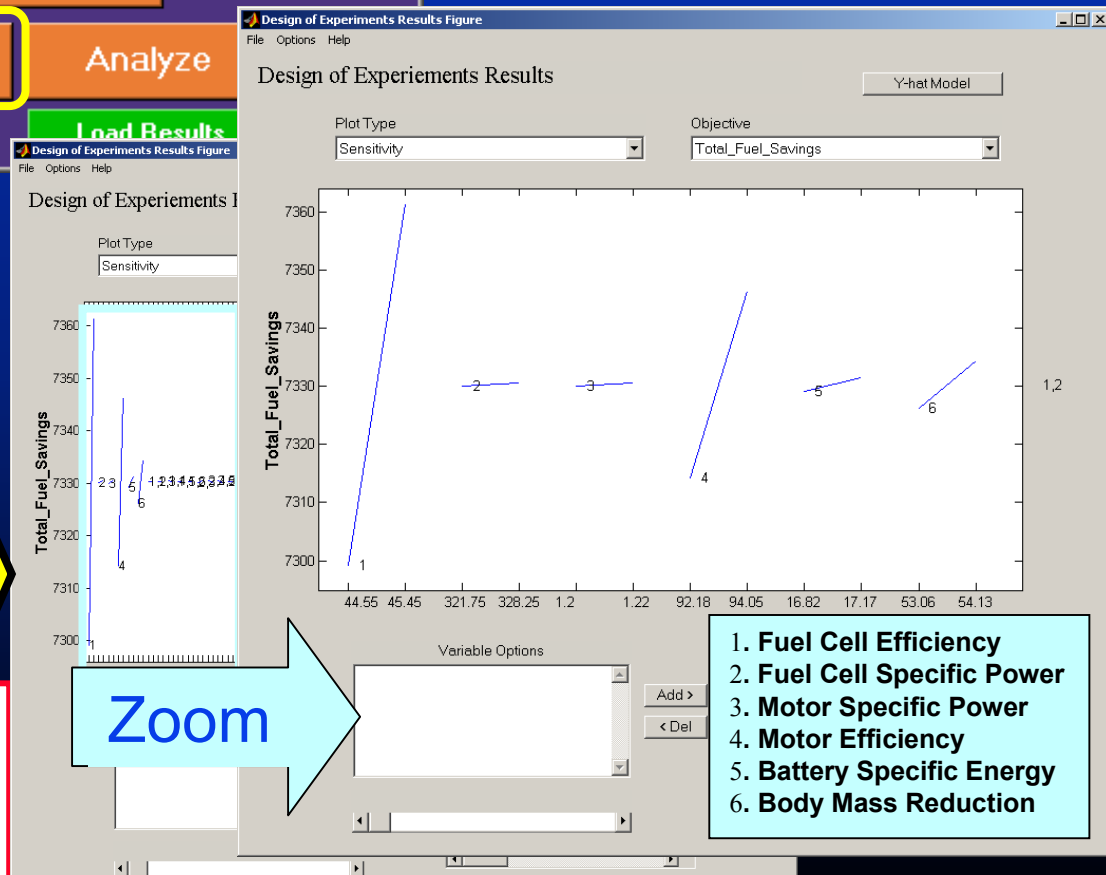
Accomplishments

Fuel Cell Targets Analyzed Using Technical Targets Tool



- Assess impact of technical team component targets at vehicle and fleet level

Technical target variation leads to sensitivity in total fuel savings

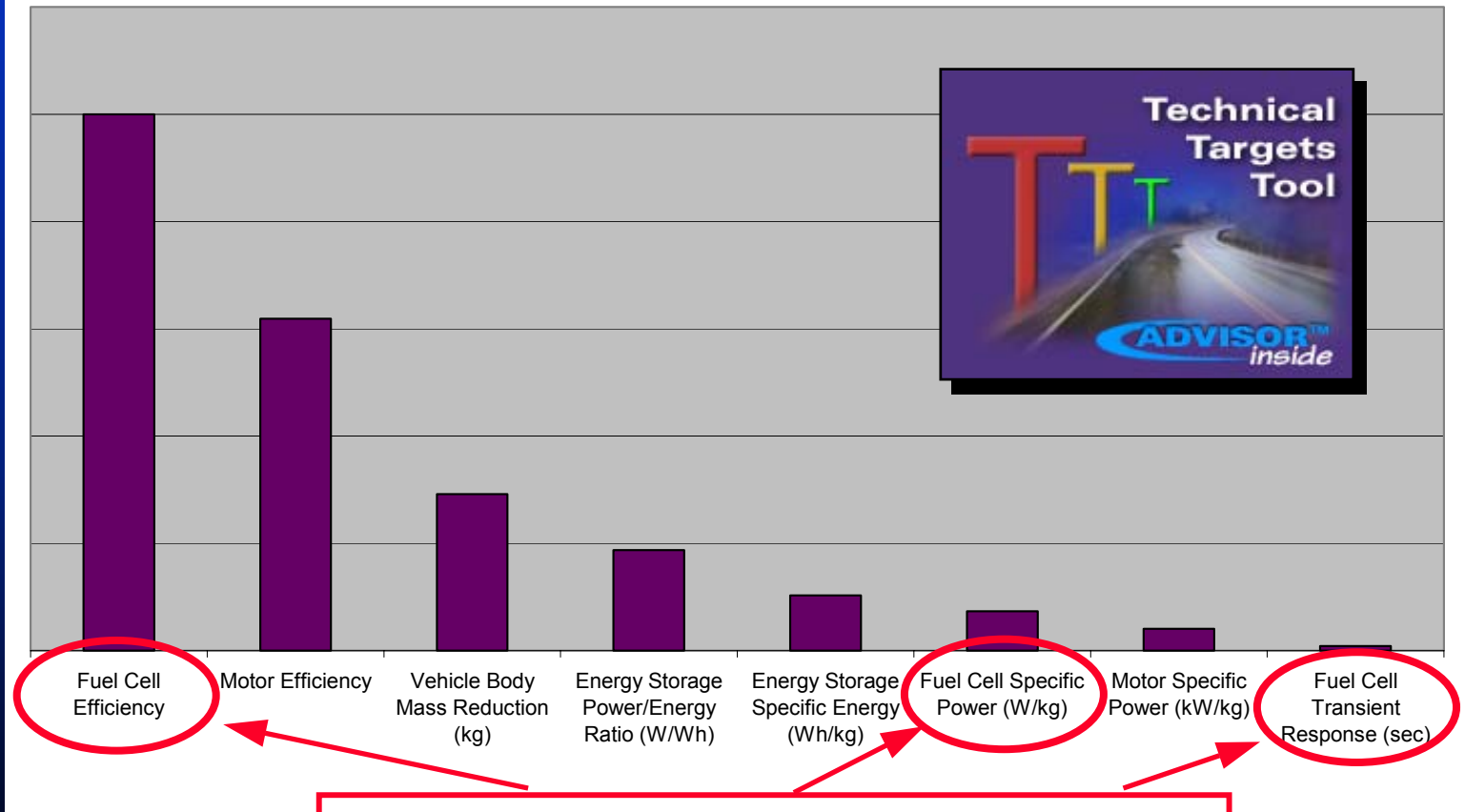


Accomplishments

T³ and DOE Highlight Relative Sensitivity of Fuel Economy

Relative Technical Target Sensitivity to Fuel Savings

Targets Varied from -1% to +1% of Nominal Target Value
Based on Optimizing for Fuel Economy and Specifying the Penetration Rate



Fuel Cell Program Targets

High Visibility of NREL's Vehicle Systems Analysis Activity Through Publications

2003-01-2253

Predicting the Fuel Economy Impact of "Cold-Start" for Reformed Gasoline Fuel Cell Vehicles

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Patrick Davis
U.S. Department of Energy

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ABSTRACT

Hydrogen fuel cell vehicle promising solution for the personal transportation. Its hydrogen and then stored in a satisfactory driving range if they can complete use ethanol. On-board reform hydrogen-rich fuel stream several stages. The high & fuel processing present a warm up the reformer quick environment. Without a spe hybridization, the reformer provide all power to move in 30 s, and 1/4 power in 5 Procedure (FTP) cycle don't meet these performance applied. Battery power an hybrid reformed gasoline & ADVISOR™ for a range, durations (10 to 120 s), economy impacts attributed of potential reformer warm a gasoline-reformed FCV or

INTRODUCTION

Known Fuel Cells, Inc. provided information for development of relationships and mathematical models of fuel cell and fuel processor.

The Wipke/AEE product is an integrated set of tools, tailored to solve design problems in specific environments and processes. The AEE allows extremely rapid iteration of system designs, with automated analysis capability. It contains a database of design and manufacturing rules, an automated geometry creation engine, links to a variety of CAE analysis packages, and a Web-browser interface.

This paper describes a prototype AEE developed for design of vehicles powered by fuel cell/fuel processor systems, including an optimization capability for packaging the propulsion components. It also describes the use of the prototype to assess the following design tasks:

Optimize the percentage of full power available for different five minutes of operation from starting

The last section of the paper briefly describes the characteristics of the final design of the AEE, which is planned for development in further phases of the contract.

PROTOTYPE AEE WORKFLOW

A simplified workflow for the prototype AEE is shown in Figure 1. The user makes several selections in order to initiate a design:

- Vehicle size (class)
- Drive cycle
- Size of the vehicle interior (roominess)
- Fuel cell system operating temperature and pressure
- Packaging options
- Stump conditions

By selecting vehicle class and interior roominess, the user has implicitly limited the amount of volume in the vehicle available for packaging the components of the fuel cell/processor system. The AEE develops models of the vehicle architecture and interior components. It then calculates the resulting volumes available in the front and rear compartments and under the passenger floor. The AEE also estimates the vehicle road load and makes use of a linkage with NREL's ADVISOR program to calculate power demand over the drive cycle.

By selecting operating pressure and temperature, the user has provided the AEE with information it will use to size the components of the propulsion system. From the selected start conditions, the AEE calculates the time to bring the system to operating temperature, and the supplemental energy, if any, required to power the vehicle during warm-up.

The AEE contains design rules that allow it to utilize three inputs to design all the required components of the vehicle and the propulsion system. Next it uses a proprietary optimization technique to attempt to package the propulsion components into the vehicle. If it cannot, it can selectively increase the vehicle dimensions until a packaging solution is found. At this point, it checks to see whether the initial assumptions it derived for vehicle weight and aerodynamic properties are still valid.

INNOVATIVE THERMAL MANAGEMENT OF FUEL CELL POWER ELECTRONICS

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Abstract

Deep at the heart of any fuel cell system lay a crucial component, the power inverter. The design of this crucial component is a challenge for fuel cell systems due to packaging, thermal and electrical constraints. Unless the inverter is adequately and uniformly cooled it will suffer material degradation and premature failure. The search for a thermally viable inverter design is one of many challenges facing the fuel cell industry today.

In this research effort several cooling techniques were considered such as pin-finned design, "cook-top" serpentine flow field, a "fish bone" fin design, high thermal conductivity graphite bus, heat pipes and aluminum extrusion with expanded metal radiator. The pin-finned design techniques were evaluated using computational fluid dynamics. In order to enable design engineers to rapidly generate optimum designs two simplified techniques were introduced using the CFD results.

1) Formulae for computing the film coefficient based on spacing, size and configuration are provided for thermal finite element analysis that includes conduction and convection. This technique is an order of magnitude faster than the CFD analysis.

2) Behavioral modeling, an optimization technique embedded within a feature based parametric CAD system is utilized to automatically size and build the solid model of the pin-finned design. The designer input is the heat that needs to be rejected and the available space. Behavioral modeling generates the design and plots the temperature distribution.

Introduction

Heat rejection from electronic components has become a problem of significant interest due to the continuing

reduction in component size and increase in function performance. It is believed that efficient cooling of the devices is a critical enabling technology for commercialization of HEV & Fuel Cell powered vehicle. The goal of this research effort is to develop a heat exchanger design to efficiently remove heat from the power electronics and reject it into the vehicle's coolant loop via uniform cooling and minimum cost, volume and pressure drop. A number of cooling techniques have recently been examined for heat rejection of power electronics with heat heats.

A heat exchanger with two flat steel plates is examined. The HOBT (modulated gate bipolar transistor) is attached to the top plate and coolant is flowing through the plate. Since there is a single inlet and outlet several variable heat

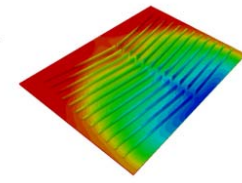


Figure 1 Cooling plate with variable orientation and height



ADVISOR 2002
Advanced Vehicle Simulator

First International Conference on
Fuel Cell Science, Engineering and Technology
April 21-23, 2003, Rochester, New York, USA

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EFFECT OF MATERIAL AND MANUFACTURING VARIATIONS ON MEMBRANE ELECTRODE ASSEMBLY PRESSURE DISTRIBUTION

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AN ANALYSIS OF WATER MANAGEMENT FOR A PEM FUEL CELL SYSTEM IN AUTOMOTIVE DRIVE CYCLES

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ABSTRACT

Low-temperature operation of a Proton Exchange Membrane (PEM) fuel cell system requires humidification of the membrane. The amount of water produced electrochemically within the fuel cell system is directly related to the system power output. In a vehicular application where the power output may vary substantially over time, it is critical that water management be addressed in the fuel cell and vehicle system design. This paper introduces the integration of a detailed fuel cell system model within a hybrid electric vehicle system model. The newly integrated models provide the capability to better understand the impacts of a variety of fuel cell and vehicle design parameters on overall system performance. Ultimately, coupling these models leads to system optimization and improved vehicle efficiency. This paper presents the initial results of a parametric study to quantify the impacts of condenser size and cathode inlet relative humidity on system water balance under realistic drive cycles in a fuel cell hybrid electric sport utility vehicle. The vehicle simulations included operation under both hot and ambient start conditions. The study results demonstrate that ambient start or aggressive drive cycles require larger condenser or water reservoirs to maintain a neutral water balance than either hot start or less aggressive drive cycles.

INTRODUCTION

Fuel cell systems have the potential to significantly increase vehicle energy efficiency and reduce regulated emissions in transportation applications. The performance of the fuel cell governs the efficiency and performance of the system. Furthermore, the performance of the proton exchange membrane (PEM) fuel cell depends on multiple operating parameters including temperature, pressure, and relative humidity. The primary loads due to the balance of plant, which provide the desired operating conditions, have a

significant influence on the overall system efficiency. Therefore, temperature, pressure, and water management affect the overall fuel cell system performance. This paper focuses on fuel cell system water management in the context of vehicle transient power requirements.

The polymer membrane in the fuel cell requires a continuous supply of water to hydrate the membrane and maintain proton conductivity. Typically, the membrane water content is managed by humidification of the inlet gas streams. A certain level of water is necessary because too much water will "flood" the membrane, blocking the transport paths of the protons, whereas too little water will create "hot spots" and reduce conductivity. Both scenarios contribute to reduced performance and lead to potential failure of the fuel cell.

The amount of water to humidify the inlet gases and maintain membrane performance can be significant. Water is also produced at the cathode as a product of the electrochemical reaction. The cathode and anode exhaust streams typically exit saturated at the fuel cell stack operating temperature. Recovery of the water vapor exiting the fuel cell is critical to supply the inlet gas humidification and to recover this water from the exit stream. The difference between the water recovered by the condenser and that required to humidify the inlet gases over time is defined as the water balance. A positive water balance means that there will be a water surplus, whereas a negative water balance leads to a water deficit. A neutral water balance over time is desirable and necessary in order to provide a self-sustaining fuel cell system.

Today's PEM fuel cell systems are designed to operate in the range of ambient pressure (100 kPa) to 300 kPa and 60-80 °C. Higher temperatures and higher pressure typically

are due to successfully

issues by focusing on their manufacturing being cost over the life by its initial design, addressed early in the design.

to deliver customer use of customer usage, and variation in mission, delivery and system as a part of design techniques as design. Traditional uncertainty through the safety factors are Ref 3), they do not and do not provide final use of available process has not been making and tedious CAD and FEA codes exploration (PTC's probabilistic systems and 7)) that make (Ref 1). Control designer can control, material selection, ranging process settings, other hand as factors

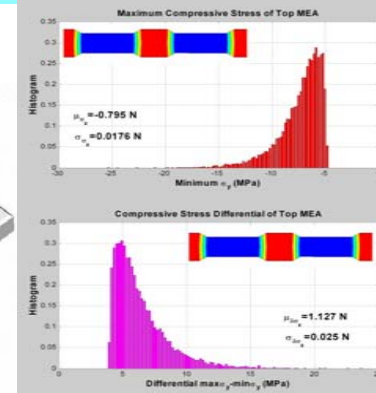
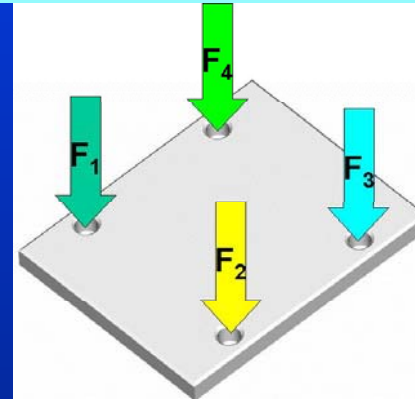
Addressing Reviewer Comments

- System cost estimates should be included in analyses
 - System costs estimated within Technical Targets Tool and recent Energy Storage System Requirements study
- Computer models should be used to evaluate fuel cell program technical targets
 - Technical Targets Tool developed and applied
- Need to accommodate fuel cell and subsystem design trade-offs
 - 2 parametric detailed fuel cell system models integrated with ADVISOR vehicle simulation tool
- Review of assumptions by industry
 - working with fuel cell, hydrogen, energy storage, and vehicle systems technical teams
 - collection of peer reviewed papers published

Recent Collaborative Projects with Industry

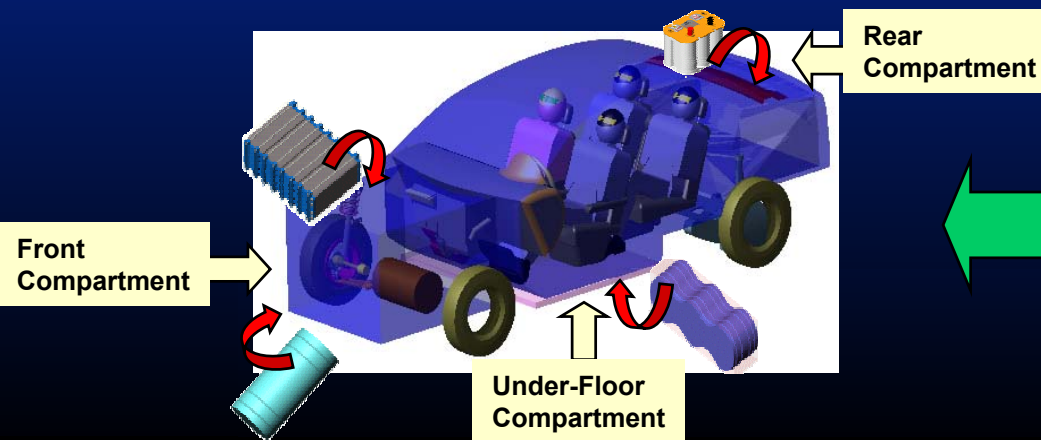
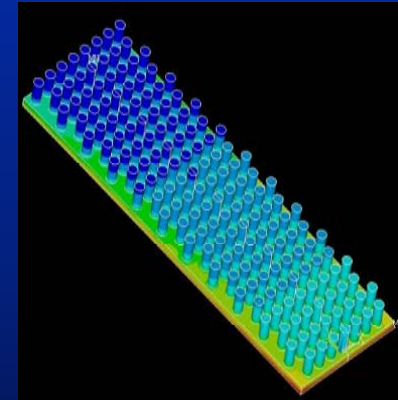
Plug Power:

- ATR thermal analysis
- Analysis of MEA pressure profiles
- End plate topology optimization
- Robust high temp. stack design



Ballard Power Systems:

- Thermal management of fuel cell power electronics



VulcanWorks/Nuvera:

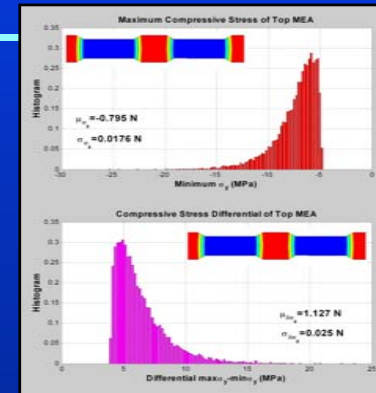
- Design and optimization of fuel cell vehicle packaging solutions

Plans and Future Milestones

- Fuel cell hybrid vehicle system optimization – working with fuel cell, energy storage, vehicle systems teams on energy storage targets for fuel cell vehicles (9/03)
- Technical Targets Tool study on sensitivity of fuel cell technical targets applied to multiple vehicle platforms (9/03)
- Complete water and thermal management analysis for fuel cell vehicles under real driving conditions (11/03)
- Validation of fuel cell models with industry partners (2/04)
- Robust design process transferred to industry to address fuel cell stack cost and durability technical barriers (9/04)

Summary

- Vehicle systems tools coupled with optimization and robust design methods are being applied to address cost and durability technical barriers



- Technical Targets Tool introduced and applied to understand sensitivity of fuel consumption to the fuel cell program technical targets

- Enhanced fuel cell system models incorporated into vehicle model to analyze thermal and water management technical barriers

